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Recent advancements in alginate-based films for active food packaging applications†

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Food packaging possesses a critical role in preserving food quality, increasing food shelf life, and reducing waste. This paper explores the potential of alginate-based food packaging as an environmentally friendly method for food-related issues. Alginate, a naturally occurring polysaccharide extracted from seaweed, has considerable potential as a sustainable packaging material due to its multifaceted properties. These properties enable alginate to encapsulate and preserve a wide range of food products effectively. Alginate food packaging has demonstrated its ability to prolong the shelf life of various food products, including fresh fruits, vegetables, meats, and baked goods. It is beneficial to maintain their moisture content and maintain oxygen levels. Furthermore, it is an effective barrier against microbial growth, while preserving the desired flavor and aroma profiles of the packaged items. Antimicrobial food packaging systems are specifically designed to inhibit microbial growth on surfaces, thus enhancing overall stability and preserving quality during storage periods. However, additional research is necessary to improve performance across various applications within the food industry. Alginate-based edible coatings have attracted significant attention due to their ability to enhance both sensory attributes, such as appearance, and mechanical properties across diverse categories including fruits, vegetables, meat, poultry, seafood, and cheese. These edible films mitigate drying effects on contents by regulating the respiration rate, ensuring optimal conditions for extended freshness and shelf life.

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Sustainability spotlight

Alginate-based food packaging derived from sustainable production has improved food preservation attributed to special barrier properties that prevent oxygen and moisture penetration. These barriers effectively extend the shelf life of the product, reducing food waste. The versatility of polymer-based food packaging systems facilitates the development of customized solutions while ensuring biocompatibility to guarantee safe food contact. Due to their biodegradable nature, alginate-based films have the potential to replace pollution-causing synthetic polymer-based films in food-packaging applications. The present review discusses alginate-based edible coatings which have gained considerable attention due to their capability in augmenting both sensory attributes such as appearance and mechanical properties across diverse food categories.

Introduction

The use of plastic packaging, a universal part of modern living, has revolutionized the way food products are stored, transported, and utilized in the food industry. The advantages of plastic packaging are abundant such as durability, economic efficiency, and adaptability for various uses. Despite its advantages, it encounters significant obstacles, particularly in regard to its environmental impact and the generation of non-degradable waste.[1,2] Certain materials, due to their long-term nature, can lead to the contamination of various ecosystems, such as marine, freshwater, and terrestrial environments, for extended periods, posing a significant ecological risk. Furthermore, the production of plastic materials is closely linked to the utilization of limited petroleum reserves. This dependence not only increases the strain on these non-renewable resources but also impacts the environment during the extraction and refinement phases.[3] The degradation of these materials over time results in the production of microplastics, which could pose a threat to both ecosystems and human health. The incorporation of harmful additives in certain types of plastic can seep into consumer goods, thereby causing concerns regarding public health and safety.[4,5] Plastic waste disposal can result in complex problems and significant financial consequences, which often lead to waste accumulation in landfills and pollution from combustion. The use of disposable plastics is widespread, leading to a culture of wastefulness, which in turn leads to more waste generation. Moreover, the production of plastics necessitates a significant energy input that results in

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the emission of greenhouse gases.[6] In response to these challenges, there are global initiatives aimed at reducing plastic usage and fostering the invention of packaging alternatives that are harmless to both the environment and human health. The objective of these initiatives is to minimize the negative consequences associated with plastic packaging.

The use of biodegradable polymers in food packaging offers a solution that is both effective and environmentally friendly and can be a viable alternative to traditional plastic packaging materials. Renewable resources like corn starch or sugar cane are often used to derive these substances, such as polylactic acid (PLA) and polyhydroxyalkanoates (PHA). The formation of natural decomposition takes place over a period of months to years, resulting in harmless byproducts like water and carbon dioxide. The sustainability of these materials is a major advantage, which reduces the need for non-renewable fossil fuels.[7]

The utilization of biodegradable packaging is prevalent in the food industry, particularly for items like fresh produce and takeaway containers. Compared with traditional plastic packaging, biodegradable alternatives contribute to a markedly reduced environmental footprint. This is primarily due to their dependence on renewable resources and their capacity to alleviate the environmental pollution that is typically a byproduct of conventional plastic usage.[8,9] Polymers derived from sustainable resources showed a promising alternative for petroleum-based plastics.[10]

Food packaging systems, which are based on sustainable polymers includes biopolymers such as PLA, polybutylene adipate terephthalate (PBAT), and synthetic polymers such as polyvinyl alcohol (PVA), have brought about a significant transformation in the field of food preservation. The distinct barrier properties of these polymers prevent the ingress of oxygen and moisture, thereby reducing the shelf life of products and reducing the consumption of food. These versatile systems facilitate the fabrication of customized solutions while ensuring biocompatibility for safe food interaction. The environmental awareness is increased and a growing demand for environmentally friendly substitutes, the introduction of polymer-based packaging allows brands to enhance their image as environmentally conscious companies.[11] Polypropylene (PP) is known for its good transparency, high melting point, and excellent barrier properties. It offers good resistance to heat, moisture, and chemicals, which make it suitable for food containers, cups, and packaging films that need to withstand high temperatures during packaging processes. High-density polyethylene (HDPE) is a thermoplastic polymer made from petroleum, known for its high strength-to-density ratio, excellent moisture resistance, and exceptional chemical resistance. HDPE provides a good barrier against moisture vapor transmission and is commonly used for packaging milk, juice, and other beverages. Medium-density polyethylene (MDPE) has a density range of 0.926–0.940 g cm^{-3} and a melting point of 126 °C. It is used in various food packaging applications.[12] Chitosan is a polysaccharide derived from chitin, found in the exoskeletons of crustaceans. Chitosan-based films and coatings exhibit antimicrobial properties and can be used for active food packaging. Starch is a polysaccharide extracted from plants like potatoes, corn, and rice. Starch-based films and coatings can be used for food packaging.[13] Gelatin is a protein derived from collagen and can be used to make biodegradable food packaging films and coatings.[14] PLA is a biodegradable aliphatic polyester derived from renewable resources like corn, sugarcane, or cassava. It is used to make food packaging materials like containers, films, and trays.[15] Compared to these synthetic polymers, alginate is a natural polymer derived from brown seaweed. It exhibits superior mucoadhesive strength, allowing it to adhere well to food surfaces. Alginate is also biodegradable and biocompatible, making it suitable for eco-friendly food packaging solutions. Alginate can be easily cross-linked with various cations to form hydrogels with tunable mechanical properties. It can also be chemically modified or blended with other natural polymers like chitosan, gelatin, and carrageenans to form composite materials with enhanced functionality for food packaging applications.[12] The versatility and favorable characteristics of alginate make it a promising candidate for developing active and intelligent food packaging systems. Alginate-based films can be integrated with functional additives like antimicrobials, antioxidants, and indicators to extend food shelf-life and monitor quality. Despite the recent advancements, there remains a need for further research and development to address potential shortcomings related to barrier properties and scalability.[16] This emphasizes the critical role of continuous innovation in sustainable packaging solutions, ensuring food safety and quality standards,[17] and accelerating their incorporation into the packaging industry.[18] Fig. 1 highlights the classification of biodegradable polymers. Polysaccharides (natural polymer) are complex carbohydrates made up of multiple sugar molecules linked together. Alginate is indeed a type of polysaccharide. It is a natural polysaccharide composed of α-D-mannuronic acid and β-L-guluronic acid derived from seaweed.

Alginate

Alginate, a polysaccharide occurring naturally, is derived from a variety of sources, and has gained considerable attention in food packaging field due to its multifaceted properties and environmental benefits.[19] Primarily, it originates from diverse species of brown seaweed such as *Laminaria hyperborea*, *Ascophyllum nodosum*, and *Macrocystis pyrifera*.[19] These sources are utilized for various applications across food, medicine, and cosmetics.[20,21] Additionally, alginate can be obtained from other algal species such as *Macrocystis pyrifera* and *Fucus vesiculosus.*[22] Certain bacteria like *Pseudomonas* sp. and *Azotobacter* sp. produce alginate for research and industrial applications.[20,22] Some fungi such as *Saprolegnia* sp., can also synthesize alginate, although this is less common.[23] Furthermore, alginate can be produced synthetically in laboratories through chemical processes.[20,21] This multifaceted biomaterial, with its diverse origins and applications, contributes significantly to environmental sustainability. A primary factor facilitating the use of alginates in food packaging is their exceptional biodegradability. Contrasting with traditional plastic packaging, which

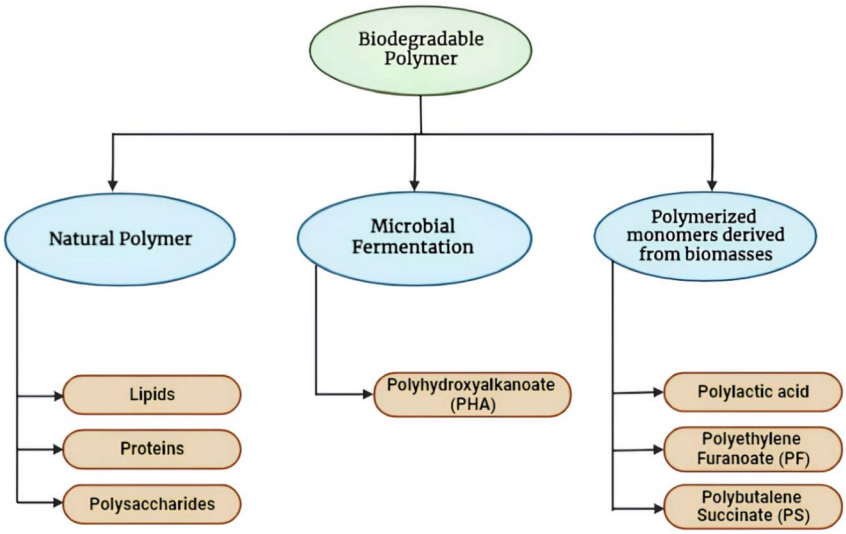

Fig. 1 Classification of biodegradable polymer.

persists in the environment for extended periods, packaging derived from alginates undergoes natural decomposition. This substantially mitigates the enduring environmental impact of food packaging, aligning with the growing global focus on sustainability and the need for eco-friendly alternatives to combat plastic pollution.[24] Alginate possesses excellent barrier characteristics against moisture and gases. It establishes a protective layer around food items, facilitating the retention of freshness and extension of shelf life. This attribute is especially advantageous for perishable goods, as it curtails food wastage and augments the overall quality of the packaged commodities. Furthermore, alginate can be easily moulded into various shapes and sizes, making it suitable for a wide range of food products. Its flexibility and versatility enable its application in innovative and customized packaging solutions.[22] Fig. 2 depicts structure of alginate.

Synthesis

The process of alginate production from brown algae involves a complex sequence of extraction and purification procedures. Initially, brown algae, such as *kelp* sp., are collected from the ocean. The alginate quality is significantly influenced by *kelp* sp. and the location of its collection. The harvested seaweed undergoes a thorough cleaning process to remove contaminants like sand, salt, and other residues. The cleaned seaweed is then subjected to maceration, a process where it is chopped into small pieces to eliminate cell structure and facilitate the extraction of alginate. The macerated seaweed is mixed with a mild alkaline solution, typically soda ash or caustic soda, to dissolve the alginate. This process can be expedited by applying heat and agitation. The mixture is subsequently filtered to separate the liquid extract, which contains the dissolved alginate, from the solid algal residue. The liquid extract is acidified, typically with sulfuric acid, which reduces the pH and solidifies the alginate into calcium alginate. Calcium chloride is added to form solid calcium alginate beads, which help in further removal of impurity. These beads are rinsed with clean water to eliminate excess calcium ions and acid, and then dried to yield calcium alginate powder. In the concluding steps, calcium alginate is transformed into sodium alginate by substituting calcium ions with sodium ions, a process typically achieved by treating it with table salt. The resultant sodium alginate is dried and pulverized into a fine powder for diverse applications.[23,25] The synthesis of alginate from seaweed algae is illustrated in Fig. 3.

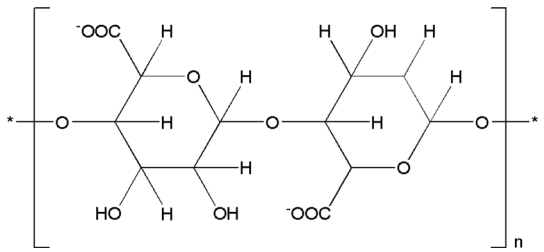

Fig. 2 Structure of alginate.

Types of food packaging

Active packaging. In contrast to conventional packaging, which simply contains and safeguards its contents, active packaging interacts with the packaged contents to enhance their longevity, safety, and overall quality. This interactive system is composed of various active elements. Oxygen scavengers are employed to decrease or eliminate oxygen levels within the package, a crucial measure for food items susceptible to oxygen-induced spoilage. Edible alginate films with oxygen scavengers extend food shelf life but face challenges. The effectiveness of oxygen scavengers is contingent upon the barrier properties of the packaging. Scavengers become rapidly saturated and lose their oxygen-absorbing capacity if packaging material allows for significant oxygen ingress. Alginate films

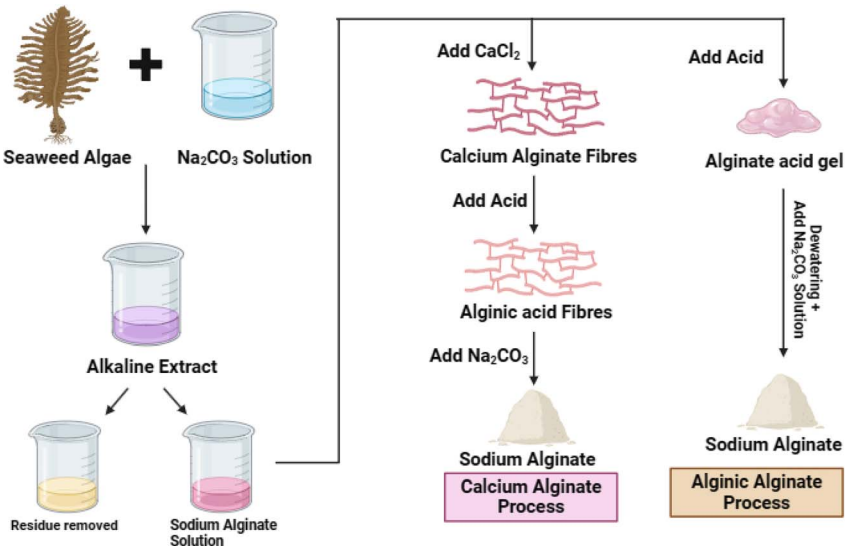

Fig. 3 Synthesis of alginate.

have limitations such as low water barrier capability, which make them less effective in high humidity conditions. Furthermore, poor ultraviolet light barrier capability can lead to degradation of the film. Moreover, these films lack antioxidant and antimicrobial activity, which cannot prevent spoilage caused by oxidation or microbial growth. Lastly, while oxygen scavengers are widely used in the food industry, consumer acceptance is more advantageous when scavengers are incorporated directly into packaging materials rather than using sachets. These challenges require continued research and development in the field of active packaging to enhance the effectiveness and consumer acceptance of oxygen scavengers in edible alginate films.[26,27] Moisture regulators control the humidity within the package, stopping potential harm or spoilage due to excess moisture. Antimicrobial agents inhibit the growth of detrimental microorganisms within the package, thereby ensuring the product's safety and extending its lifespan. Temperature monitors supply data about the package internal temperature, ensuring ideal storage conditions for the product. Active packaging systems, in essence, offer a proactive strategy to uphold product quality and safety. By interacting with the product, these systems ensure that the contents remain in peak condition until it reach the end consumer. Controlling moisture is necessary to prevent mold growth. Introducing packaging materials with antimicrobial features can extend the products shelf life. Time–temperature monitors are essential for precise temperature monitoring, especially for products like vaccines or certain foods that necessitate specific storage conditions. Moreover, active packaging promotes sustainability by reducing food waste and can even incorporate smart technology for real-time condition monitoring. These advancements in materials and technology render active packaging a crucial element in enhancing product quality, safety, and environmental performance.[28]

Intelligent packaging. Intelligent packaging represents a transformative progression in the packaging industry, employing advanced technologies to surmount the limitations of conventional packaging. This significant transition offers an array of advantages to both consumers and producers. It enables the real-time information of crucial product details, including freshness and expiry dates, thereby empowering consumers to make well-informed choices. This not only enhances consumer trust and satisfaction but also optimizes supply chain processes by providing valuable insights into product status and handling conditions.[29] Furthermore, intelligent packaging enhances security through features such as QR codes, RFID tags, and holograms, which are employed for product authentication and safeguarding against interference. These features also enhance traceability, enabling users to follow a product's trajectory from manufacture to distribution. Intelligent packaging possesses the capability to supervise environmental factors such as temperature and humidity to maintain quality. Its capacity to interface with smartphones, issue notifications to prevent wastage, and enhance supply chain procedures renders intelligent packaging multifaceted and appealing to consumers.[30] Moreover, intelligent packaging boost sustainability efforts by employing eco-friendly materials and minimizing surplus packaging. For producers, the information produced by intelligent packaging offers crucial understanding into consumer behaviour and preferences, paving the way for continuous improvement and innovation in the industry.[31] Fig. 4 summarizes advantages of alginate-based food packaging.

Synthesis of edible films

The formation of edible films involves a variety of methods such as coacervation (either straightforward or intricate), gelation or heat-driven coagulation, solvent casting, and extrusion.[32] Simple coacervation is a procedure that involves a phase transition or precipitation in a hydrocolloid distributed in water, enabled by diverse methods such as the evaporation of

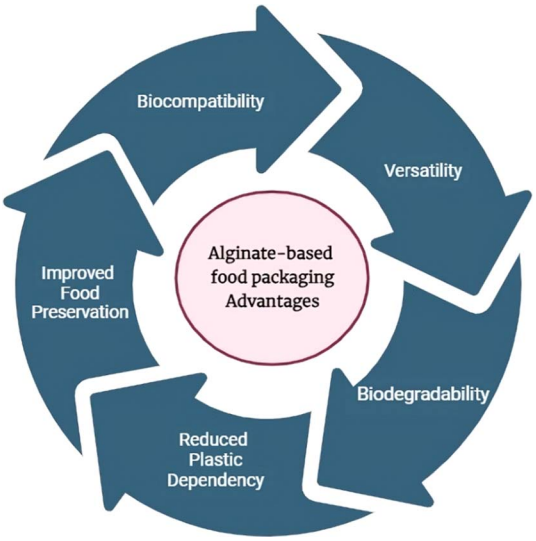

Fig. 4 Advantages of alginate-based food packaging.[19,24]

a solvent, the introduction of a water-soluble nonelectrolyte, or the adjustment of pH. Complex coacervation pertains to the precipitation of a polymer complex through the merging of two hydrocolloid solutions bearing contrasting electron charges. Gelation or thermal coagulation is a process of precipitation where a macromolecule undergoes heating to disintegrate it, or a hydrocolloid dispersion is subjected to cooling.[33] Solvent casting is a technique utilized to produce flexible, thin, and biodegradable edible films. This is achieved by integrating appropriate edible substances with a solvent that adheres to food safety regulations. The mixture thus formed yields a homogenous, thin film which, upon drying, results in the intended film.[34] The film acts as a safeguard for a variety of food items, prolonging their shelf life and aiding in waste minimization.[35] The extrusion process produces edible films that are thin, biodegradable, and suitable for consumption. Edible materials are incorporated and then subjected to controlled heat and pressure through extrusion. Post-extrusion, the substance is chilled to harden and subsequently shaped into the preferred configuration. These procedures are similar to those employed for thermoplastic films, particularly solvent casting, and extrusion, although the precise circumstances under which these processes are executed can differ.[28,29] Fig. 5 summarizes edible film synthesis methods.

Coating methods

The process of preparing edible coatings and ensuring their adherence to the food surface is vitally significant. These coatings are typically manufactured using three distinct techniques: dipping, spraying, and vacuum impregnation. Dipping, a prevalent method in food packaging, involves submerging the food item in a specially designed solution that often includes additives and edible substances. This combination forms a protective barrier around the food item.[36] Post-dipping, the surplus solution is permitted to dissipate, leading to the drying and solidification of the coated items. This technique is frequently utilized in the processing and preservation of an array of products, such as fruits, vegetables, and sweets. The end product exhibits a wide range of alternatives to enhance freshness, visual appeal, and durability. Contingent on the particular requirements of the product, the dipping coating procedure provides a broad spectrum of materials that can be applied either manually or *via* automated mechanisms.[37] The procedure of spray coating involves the application of a uniform protective layer or coating to food items by spraying onto the packaging. This procedure encompasses multiple stages, including the selection of an appropriate coating substance, the formulation of a coating solution, the application of the solution to the food item *via* spraying, the drying or solidification of the coating, and ultimately, the packaging of the coated food item.[37] This technique is adaptable and can be efficiently employed on an extensive range of food products. It fulfils multiple objectives, including enhancing visual appeal, prolonging product longevity, and safeguarding against flavor degradation and moisture intrusion.[38] Vacuum impregnation is a technique utilized in food packaging where a particular liquid or solution is introduced into the food *via* negative pressure. The procedure encompasses several stages: choosing an appropriate coating substance, formulating a solution, positioning the food in a vacuum chamber, infusing the solution into the food, and ultimately distributing the infused food. This technique enables the incorporation of various ingredients into foods, such as flavourings,

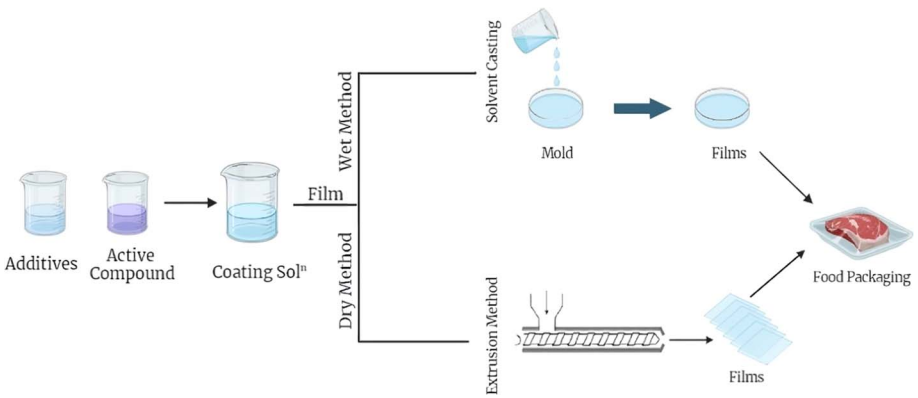

Fig. 5 Edible film synthesis methods.

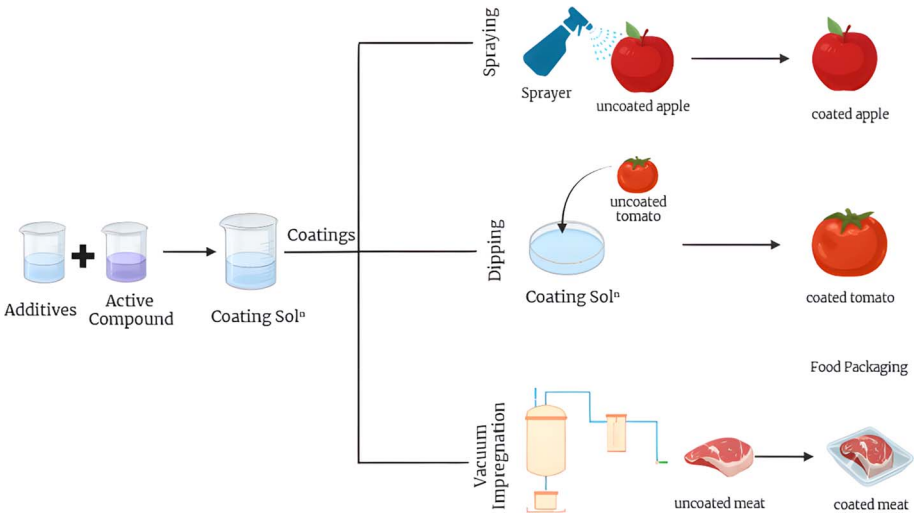

Fig. 6 Coating application methods.

colorants, or preservatives. It enhances the product's shelf life and improves its sensory attributes. Vacuum impregnation is a prevalent method in the food industry with a multitude of applications for diverse types of products.[39] Fig. 6 depicts coating application methods.

Crosslinking

The process of crosslinking alginate is a prevalent method employed to enhance its characteristics for a range of uses, including but not limited to, food packaging. The crosslinked alginate undergoes a series of transformations, culminating in a material that is both strong and resistant, thereby improving its durability for packaging applications. Alginate crosslinking can be achieved through the use of chemical agents. Ca^{2+} ions, which are frequently used as crosslinking agents, can be incorporated by immersing the material in a $CaCl_2$ solution. This technique aids in the formation of a robust and long-lasting alginate matrix.[40] Physical strategies, including freeze–thaw cycles or the utilization of thermosensitive polymers, can be applied for the crosslinking of alginate. These methodologies can impart beneficial attributes to substances used in food packaging, encompassing the establishment of reversible crosslinks.[41] Blending alginate with various polymers, such as starch and PVA, facilitates the production of composites. These composites exhibit improved mechanical strength and enhanced barrier properties.[42] The blending process allows properties to be tailored to the precise specifications required for food packaging. The technique, which employs electrostatic forces to facilitate the crosslinking of alginate, is called electrostatic gelation. Alginate can be combined with molecules or polymers that possess opposite charges, such as proteins or chitosan, to form a gel-like structure. This method has the potential to enhance the mechanical strength and barrier properties of alginate films.[43] For crosslinking alginate for food packaging, it is crucial to consider specific packaging requirements such as barrier properties, mechanical strength, and biodegradability.[42] The process involves incorporating gelling ions into the alginate solution to form a hydrogel suitable for packaging. This can be achieved *via* two distinct techniques: external and internal gelation. These techniques provide precise control over the gelation process, enabling the formulation of alginate properties to meet specific packaging requirements. This ensures that the final product is not only effective but also environmentally friendly due to its biodegradability.[44] In the conventional external gelation method, an alginate solution is exposed to a solution with gelling ions. The carboxyl groups of the guluronic acid residues react immediately with the Ca^{2+} ions and form an irreversible hydrogel as a result of ion diffusion. In internal gelation, alginate solutions are exposed to an insoluble source of gelling ions.[45] In addition, the pH is reduced by the addition of organic acids or by the rapid hydrolysis of lactones, which releases the gelling ions.[46] In contrast, internal gelation results in more homogeneous, although less compact, gel matrices with greater pore diameters than external gelation. This is mainly due to the presence of acid, which causes the displacement of Ca^{2+} ions by H^+ ions.[47] Khwaldia *et al.* synthesized a film by crosslinking diphenyl phosphine-ethylene (DPPE) with alginate at varying concentrations (10%, 20%, 30%, and 40% w/w). The DPPE inclusion led to reduced solubility and wettability. The 10% DPPE film exhibited improved water vapor barrier properties, tensile strength, and elongation at break. However, the 40% DPPE film showed the least phenolic content, DPPH (2,2-diphenyl-1-picrylhydrazyl) scavenging activity and FRAP (ferric reduction activity potential) retention after three months of storage.[48] Maziyar Makaremi *et al.*, study showed that the bio composite samples were subjected to a two-step crosslinking and rewetting process. Initially, the specimens were crosslinked in a solution containing 2% $CaCl_2$, a process that was accomplished within a span of 2 minutes. Subsequently, the crosslinking was reversed using a 5% sodium citrate solution. However, the duration required to reverse the crosslinking was not constant and varied depending on the unique composition of each sample.[49] Parreidt *et al.*

demonstrated a crosslinking method for alginate, significantly influenced the thickness of the resulting films. The technique involved immersing the alginate gel in a crosslinking solution, yielding thinner films than those obtained by adding the crosslinking agent directly to the alginate solution. The crosslinking process, involving the interaction of alginate with Ca^{2+} ions, resulted in the formation of coatings and films. These crosslinked alginate coatings and films have demonstrated effectiveness in enhancing food product quality and extending shelf life.[50] Singh *et al.* conducted a study on the fabrication of crosslinked polymers, primarily composed of pectin and sodium alginate. The crosslinking process was performed using environmentally friendly acids, specifically citric and tartaric acid. The study evaluated the effectiveness of these materials for food packaging applications, particularly for chocolate and Indian vegetable cakes, with the aim of prolonging their shelf life using innovative packaging materials.[51]

Mechanical properties. Alginate-based films, known for their mechanical strength and flexibility, are ideal for food packaging applications. Their properties can be enhanced by cross-linking with xylitol and D-mannitol, resulting in increased tensile strength and more rigid, tough, and stretchable films.[52] Alginate films, excellent oxygen barriers, exhibit poor moisture resistance and low water solubility, posing challenges for food packaging applications.[53,54] Alginate films, characterized by their transparent, fragile, and rigid nature, possess the benefit of being devoid of taste and smell, a feature that is advantageous for food packaging purposes.[53] Cross-linking can alter the mechanical properties of alginate films. For instance, D-mannitol cross-linked films exhibit a slightly higher Young's modulus than xylitol, while xylitol cross-linking results in a greater elongation at break (E%). Alginate-based hydrogel films, serves as substance carriers, have release properties dependent on the cross-linker type.[54]

Optical properties. Alginate-based films, with their unique optical properties, are becoming popular in food packaging. Their transparency allows product visibility to be influenced by consumer preferences. The film color can be altered using natural colorants such as curcumin, which enhances aesthetics and indicated food properties.[55] These films exhibit excellent UV-blocking properties, which is crucial for protecting light-sensitive foods. Additionally, alginate, whey protein, and curcumin films demonstrated significant UV-blocking efficiency. Furthermore, smart packaging applications can utilize curcumin-containing films, which alter color in response to ammonia vapor, indicating food freshness or contamination.[56,57] Thus, the optical properties of alginate-based films not only provide a protective barrier, but also enhance the visual appeal and functionality of packaging.

Water absorption properties. Alginate-based films, possess unique hygroscopic properties, play a crucial role in food packaging. These films absorb and retain moisture, offer temporary protection against food dehydration. These films are capable of absorbing water up to 200–300 times their weight, assist in preserving the moisture content of food.[55] However, such absorption may cause swelling, which leads to increased water vapor transmission and uptake, which potentially impact the mechanical properties of the film. Water-resistance can be introduced through internal and external gelation with $CaCl_2$, thereby reducing the hydrophilic nature of the films.[58,59] The water absorption properties of alginate-based films offer advantages, but also pose challenges, which make it essential to consider these properties while designing alginate-based films for food packaging applications.

Barrier properties. Food packaging derived from alginate offers numerous advantages for an extensive array of food items. Its inherent characteristics, including its ability to act as a water vapor barrier, preserve food freshness, resist oil and fat, block UV radiation, exhibit mechanical robustness, and biodegrade, render it an appropriate choice for food packaging applications. A multitude of research efforts have been undertaken to augment the attributes of films based on alginate. Enhancements to these films encompass elevated thermal and water vapor permeability, UV barrier properties,[60] oxygen barrier attributes, mechanical strength, and antimicrobial properties.[50] These films have demonstrated their effectiveness in maintaining the quality of various food items and extending their shelf life. This new approach could potentially provide a fresh solution for safeguarding the freshness and quality of foodstuffs, while promoting environmental sustainability.[61]

Additives

Antioxidants: enhancing shelf life. Alginate-based food packaging materials are known for their considerable antioxidant activity due to various key factors. Alginate has an inherent antioxidant value due to the manifestation of bioactive compounds such as phenolic compounds and flavonoids. These components are capable of neutralizing free radicals and thus possess antioxidant properties. Furthermore, food packaging manufacturers often use additional antioxidants in alginate-based films. These additives usually contain compounds such as ascorbic acid, tocopherol, and plant extracts such as *Rosmarinus officinalis* extract. The inclusion of these additives is intended to increase the overall antioxidant capacity of the packaging material.[62] Moreover, alginate matrices provide the advantage of controlled release of antioxidants. This mechanism facilitates a gradual and sustained release of antioxidants, effectively extending the shelf life of packaged foods by reducing oxidative damage. Finally, the chelating capabilities of alginate are remarkable for various food packaging applications. Alginate contains functional groups capable of forming coordination complexes or complexes with metal ions, such as iron and copper. These metal ions often act as catalysts for oxidative reactions in foods. The effective binding of these ions by alginate packaging reduces the rate of oxidation of foods and thus improves their suitability for food preservation. Li *et al.*, developed an environmentally friendly film packaging using citrus pectin, and sodium alginate. The films were prepared with different concentrations of pterostilbene (PTE), ranging from 0.2 to 3.2 mM. The films exhibited satisfactory tensile strength and elongation, which decreased with the addition of PTE. However, the addition of PTE resulted in increased moisture resistance

and improved antioxidant properties. Crosslinking with $CaCl_2$ resulted in reduced water solubility and improved thermal stability. The developed films exhibited significant potential as antioxidant packaging materials.[63] Gubitosa *et al.*, developed water-resistant films for food packaging using sodium alginate. These films showed a decrease in hydrophilicity and high stability at elevated temperatures and varying pH. However, the film swelled on exposure to concentrated salt solutions. In addition, grape pomace waste extract was used to improve UV light shielding and antioxidant properties. These films were proposed to be used to protect food from light-induced spoilage while being waterproof and stable.[64] Alves *et al.*, developed bionanocomposite films by incorporating different amounts of reduced graphene oxide (rGO) or a combination of zinc oxide and rGO (ZnO-rGO) into an alginate matrix using a solvent casting technique. Sepiolite was used to enhance the compatibility between reduced graphene oxide and the hydrophilic matrix. The addition of fillers maintained the low water solubility achieved by the $CaCl_2$ treatment but resulted in a decrease in mechanical strength and a slight increase in water vapor permeability and wettability. The introduction of ZnO-rGO resulted in a significant improvement of the electrical conductivity, especially in through-plane measurements. Films containing a blend of 50% ZnO-rGO exhibited remarkable antioxidant and antibacterial properties, suggested their potential applicability in food preservation and low-temperature food sterilization in packaging applications.[65]

Antimicrobial agents: preserving food quality. Food packaging materials derived from alginate have shown antimicrobial activity. Alginate when combined or modified with other substance possesses antimicrobial property.[66] In addition, alginate matrices can be enriched with antimicrobial agents such as essential oils, silver nanoparticles, or bacteriocins. These active ingredients are gradually released and act as a barrier against the growth of bacteria, molds and yeasts that could spoil or contaminate the packaged food. In addition, alginate films can be developed specifically as "active packaging". This form of packaging performs functions such as oxygen absorption or moisture absorption, reducing conditions favorable to the growth of microorganisms. The use of a multifaceted strategy highlighted the potential of alginate-based antimicrobial food packaging to improve food preservation and safety.

Li *et al.* concentrated on fabricating biodegradable food packaging materials utilizing sodium alginate and tannic acid. The study demonstrated that elevated tannic acid concentrations in the films enhanced water vapor barrier properties and antioxidant activity, although with a minor reduction in light transmission. The films demonstrated UV light blocking capabilities and demonstrated enhanced antimicrobial activity against *Escherichia coli*.[67] Chinnaiah *et al.* engineered a polymer membrane by incorporating leaf extract of *Datura metel* L. and sodium alginate *via* the solution casting method. The resultant membrane showed an ionic conductivity of 2.18×10^{-4} S cm^{-1} and a peak specific capacitance of 131 F g^{-1} at a current density of 0.2 A g^{-1}, while also demonstrated substantial antimicrobial activity against human pathogens. These findings indicated that the fabricated membranes could be used as solid electrolytes in supercapacitor devices and as antimicrobial components in food packaging.[68] Carvalho *et al.* formulated a polyelectrolyte film by combining sodium alginate and poly(diallyl dimethylammonium chloride), PDDA, to generate a surface possessing antimicrobial properties for food packaging. The films showed a compact structure and exhibited ionic interaction between sodium alginate and PDDA. PDDA enhanced the mechanical robustness and thermal stability of the films due to its hydrophilic nature. The chosen film showcased considerable success in reducing 99.8% of SARS-CoV-2 within a minute of exposure. Additionally, it demonstrated an inhibitory effect against *Staphylococcus aureus* and *Escherichia coli*.[69] Wei *et al.* developed an intelligent packaging film capable of real-time food freshness monitoring. Cubic cobalt metal–organic framework (Co-MOF) microcrystals, which are ammonia-sensitive and possess antibacterial properties, were immobilized in a sodium alginate matrix. The sodium alginate-based films, with varying cobalt imidazole content (0.5%, 1.0%, and 2.0%), exhibited enhanced mechanical strength, toughness, oxygen/water barrier, UV-blocking capability, and antibacterial activity. The films, being ammonia sensitive and color stable, are deemed suitable for detecting shrimp spoilage based on observable color alterations.[70]

Appendini *et al.* emphasizes the role of packaging technologies in preserving food quality and safety. The research advocates for antimicrobial packaging materials to extend shelf life and limit pathogens. These materials work by inhibiting microorganism growth in the food. Factors like water activity, oxygen consumption, and temperature imbalances can cause food spoilage. The use of engineered biopolymers with antimicrobial properties can help reduce oxygen permeability and inhibit microbial growth on the food surface. Antimicrobials are released over time to maintain control of microbial activity.[71] Studies showed that incorporation of natural antimicrobials into alginate-based biofilms for food packaging applications. It showed that incorporating white ginseng extract into alginate films can impart antimicrobial properties. Alginate is used to encapsulate lactic acid bacteria enhancing their ability to inhibit foodborne pathogens in biofilms for ready-to-eat foods, and when combined with garlic oil in films, it improves their natural antibacterial properties.[72] Biopolymers mixed with water, ethanol, and other solvents are also used as anti-microbial components in packaging.[73] Researchers have demonstrated the antibacterial effectiveness of sodium alginate, which is combined with nanoparticles, against experimental strains. Furthermore, the nanoparticle-infused film demonstrated an improvement in the shelf-life stability of pears and carrots, as demonstrated by the preservation of soluble protein content and a decrease in weight during storage.[74]

Starch or protein-based biopolymers are recognized for their antibacterial properties in packaging applications.[75] Notably, additives such as lysozyme, benzoic acid, propionic acid, lactic acid, ascorbic acid, and nisin enhance the antimicrobial efficacy of biofilms.[76] The effectiveness of these materials, however, is contingent upon the storage and distribution systems employed. Recent studies suggested that incorporated alginate

with antimicrobial agents into biopolymers may prolong the shelf life of meat products.[77] Moreover, biopolymer films containing antibacterial agents have demonstrated the ability to inhibit the growth of pathogens like *Listeria monocytogenes* and *Escherichia coli*, thereby safeguarding food from contamination.[78] While some biopolymer packaging includes mechanisms to hinder microbial proliferation within the food, it is crucial that these antimicrobial agents do not adulterate the food product. However, the potential migration of these substances from the packaging to the food requires thorough research prior to market release.[79] Appendini *et al.* study concluded that calcium alginates increased the growth of microbes such as coliform bacterial strain on beef and other natural flora.[71] The presence of $CaCl_2$ in the biofilm has been attributed to such a possibility.[80] Biofilm efficacy in antimicrobial properties varies, with sodium alginate demonstrated greater inhibition than κ-carrageenan due to its superior moisture absorption, facilitating faster antimicrobial agent delivery into the food matrix. This approach is known as "smart packaging".[81] The incorporation of organic acids in films is reported to prevent beef by reducing the growth of microbes like *L. monocytogenes*, *Salmonella typhimurium*, and *E. coli*.[82] Biofilms exhibited thermoresistance, attributed to *Pediococcus* sp. *bacteriocins*, possess chelating properties effective against *L. monocytogenes*.[83] Alginate films, particularly in combination with PVA and zein, effectively encapsulate and deliver antimicrobials like lysozyme and nisin. This enhances food preservation and extends shelf life by promoting the antimicrobial action of these natural compounds.[84,85] Mecitoglu *et al.*, incorporated lactoperoxidase (LPS), an enzyme from bovine milk, into alginate films. Zein films consisting of partially purified lysozyme demonstrated antimicrobial effects on *Bacillus subtilis* and *Lactobacillus plantarum*. The study showed that the partially purified lysozyme used in antimicrobial packaging to enhance food safety.[86] Researchers used polyelectrolyte packaging with antimicrobial properties using sodium alginate, and cationic starch. These films showed excellent thermal stability and improved antimicrobial effect. The finding revealed that polyelectrolyte sodium alginate packaging has excellent antimicrobial properties and can be used as a suitable food packaging material.[87]

Plasticizers: enhancing flexibility. Plasticizers are indeed commonly used in alginate-based food packaging to improve the flexibility and mechanical properties of the films. Approved plasticizers include glycerin, sorbitol, propylene glycol, polyethylene glycol, triacetin, acetylated monoglycerides, citrate esters, and lactic acid esters of monoglycerides. The choice of plasticizer depends on the particular application and the desired properties of the film.[88] Ramakrishnan *et al.*, prepared bio-based films by combining kondagogu gum and sodium alginate using glycerol as a plasticizer. The blended films exhibited a water contact angle of 81° and high tensile strength (up to 24 MPa) and showed promising properties for environmentally friendly and sustainable food packaging.[89] Amariei *et al.*, developed biodegradable materials made of polysaccharides (alginate, agar) and glycerol as plasticizers to replace polyethylene food packaging. The addition of ascorbic acid increased tensile strength, transparency and barrier properties to oxygen and water vapor. The addition of $CaCl_2$, on the other hand, improved hardness, tensile strength, and opacity.[90] Yang *et al.*, conducted a study involving grafting of methyl methacrylate (MMA) in water onto alginate using ammonium persulfate initiators under a nitrogen gas atmosphere. This process resulted in a thin, transparent, and robust alginate film grafted with polymethyl methacrylate (PMMA). Transparent films were obtained for the MMA/SA (methyl methacrylate/Styrene acrylate) ratio was less than 8.64%. PMMA grafting increased tensile strength by 205.3% and elongation at break by 41.7% with an MMA/SA ratio of 0.3.[91]

Nanostructures: enhancing barrier properties. Nanostructures such as nanoparticles can potentially be used as additives in alginate-based food packaging to improve various aspects of the functionality of the packaging material. Examples include the use of nano clays to improve mechanical and barrier properties, silver nanoparticles for their antimicrobial properties, nano emulsions for controlled release of flavor and color, and nanocomposites to reinforce films.[92] Yadav *et al.* developed eco-friendly bio nanocomposite films composed of cellulose nanocrystals, silver nanoparticles, and alginate.[61] Frank *et al.*, developed alginate-based antibacterial films by incorporating nano emulsions of cinnamon essential oil (CEO-NE). The most effective antibacterial films contained 20% CEO-NE and showed significant inhibition against various bacteria.[93] Yang *et al.*, developed bilayer films of sodium alginate and tea tree essential oil nano emulsion (TEON). These films with different contents of TiO_2 nanoparticles exhibited excellent UV blocking and enhanced water vapor and oxygen barrier properties.[94] However, for using nanostructures in food packaging, a comprehensive evaluation of safety protocols, regulatory compliance, and potential migration of nanoparticles into food is essential. Food safety regulations are essential in these applications.

Colorants and flavors: improving visual appeal and taste. Additives such as colorants and flavourings can be used to enhance the visual appeal and taste of packaged food. Natural food colouring from sources such as beetroot or turmeric, and extracts from *spirulina* sp., anthocyanins, and chlorophyll, can be added to films. Natural and synthetic compounds such as plant extracts, essential oils, herbs, flavor, sweeteners, and spices can provide taste and aroma to packaging materials. However, the choice of additives should be based on the desired sensory properties of the food and should comply with regulatory requirements for food additives. A detailed evaluation of concentration levels is crucial to ensure the effectiveness and safety of the package. This method allows for a more intense sensory experience while ensuring food safety and quality.[95]

Alginate-based natural polymer composites for green packaging. Deepa *et al.* reported that incorporating 2,2,6,6-tetramethylpiperidine-*N*-oxyl-oxidized cellulose nanocrystals (TEMPO-OCNC) into the sodium alginate matrix *via* ultrasonication enhances the XRD pattern diffraction peak, indicated a more homogeneous dispersion of nanocrystal particles. The ultrasonication process reduces surface roughness, minimizes TEMPO-OCNC agglomeration, and promotes hydrogen bonding, fostering strong interfacial interactions between TEMPO-OCNC and sodium alginate. The inclusion of 10%

TEMPO-OCNC raises the glass transition temperature to 25.88 °C, which suggested a crosslink complex formation with alginate components. This resulted in a higher storage modulus (4.499 GPa) than pure SA, due to the formation of a 3D network of interconnecting layers in the polymer matrix, enhancing the intermolecular hydrogen bonding between TEMPO-OCNC and SA.[96] Ma *et al.* observed that the XRD peak of cellulose nanocrystal (CE-NC) vanishes in most composite fibers, which indicated that CE-NC dispersion in alginate composites was effective. As CE-NC content increases, both tensile strength and elongation at break of the CE-NC alginate fiber composite initially increase, peaking at 0.5 wt% loading. Water absorbency of the composite fibers also increases with CE-NC content, reaching a maximum of 1333% at 1.0 wt% of CNC. The addition of a small amount of CE-NC disrupts H-bonding between alginate, which enhances the fibers water absorbency.[97] Abdollahi *et al.* developed alginate/cellulose nanocrystals (CNC) composite was reduced from 99.55% to 77.49%, due to strong hydrogen bonding between the biopolymer hydroxyl group and nanofiller. This interaction enhances matrix cohesiveness and reduces water sensitivity. The incorporation of CNC into the alginate matrix led to an approximately 18% reduction in water vapor permeability (WVP), likely due to the difficult path formed by the impermeable crystalline CNC layers within the matrix. Tensile strength and Young's modulus of the alginate/CNC improved as a result of their similar polysaccharide structures and the uniform dispersion of high-performance CNC fillers in the biopolymer matrix, which promoted effective interfacial hydrogen and ionic interactions with the alginate molecules functional group.[98] Mahcene *et al.* observed that essential oil (EO) inclusion in sodium alginate films led to a slight decrease in glass transition and melting temperatures, but an increase in enthalpy of heating values. The films exhibited reduced moisture content, water vapor permeability (WVP), and oxygen permeability due to EO-induced changes in hydrophilicity. Tensile strength dropped from 2.14 MPa to 0.71 MPa, attributed to EO weakening intermolecular forces and increasing free volume. The films demonstrated significant antibacterial activity against foodborne pathogens and strong DPPH radical scavenging capability.[99] Aziz *et al.* found that addition castor oil (CO) to sodium alginate improved thermal stability, evidenced by an increased maximum decomposition rate temperature and reduced mass loss. Tensile strength rose with up to 1% CO, due to enhanced hydrogen bonding and electrostatic attraction. Elongation at break also increased, as CO acted as a plasticizer, promoting chain mobility. WVP of the films significantly decreased with CO, attributed to increased hydrophobicity and crosslinking density.[100] Li *et al.* developed chitosan-alginate films using layer-by-layer assembly and ferulic acid crosslinking. The tensile strength of the resulting film increased by 38.2% compared to the original, and its opacity rose by 189.26%, due to improved molecular interaction and a denser structure. Water vapor transmission and solubility decreased by 70.7% and 68.8% respectively, which indicated enhanced water resistance.[101] Wang *et al.* reported that adding carboxymethyl chitosan-ZnO nanoparticles (CTS/ZnO) to chitosan/SA films led to a rougher surface and increased thickness. The tensile strength rose with CTS-ZnO content due to increased internal friction, while elongation at break dropped to 25.32% due to altered hydrogen bonding. Water solubility decreased to 39.84% with CTS-ZnO, likely due to restricted SA chain movement. WVP also decreased with CTS-ZnO, attributed to its superior water resistance and the development of complex paths for water molecules. The antibacterial effect of the films was significantly enhanced with increased CTS-ZnO content.[102] de Oliveira *et al.* found that incorporation of cottonseed protein hydrolysates (CSPH) into SA films increased film thickness by 10 μm, 50 μm, and 110 μm for 0.15%, 0.30%, and 0.60% protein hydrolysates respectively, due to increased solids content post-CSPH incorporation. However, CSPH incorporation did not alter the film moisture content. The biodegradability of the SA films remained largely unaffected by CSPH, with values between 95.75% and 98.01%, which suggested CSPH potential for rapid microbial action and biodegradation. The WVP of the film increased significantly by 74.2% for the film with 0.60% CSPH, likely due to the plasticizing effect of CSPH increasing the free volume of the film matrix and rendering the network less dense and more permeable. The water solubility of the film exceeded 98% post-PH incorporation, attributed to the hydrophilic nature of SA and CSPH.[103] Iswarya *et al.* formulated sodium alginate/hydroxyapatite/graphene nanoplatelets bio nanocomposite films, demonstrated good biocompatibility for bone tissue engineering. XRD and FTIR analyses confirmed the presence and interaction of the components. SEM images showed the morphology of the fillers and films. Tensile strength improved with varying graphene concentrations, peaking at 0.5 wt% graphene and 10 wt% hydroxyapatite, but decreased at higher graphene loadings. The film tensile strength increased by 17% with 10% hydroxyapatite and by 99% with an additional 0.5% graphene. Biological tests confirmed the film biocompatibility, suggested the potential for enhancing food packaging durability.[104]

Applications. Table 1 summarises the application of alginate coating on food products. Table 2 describes the composition of the functional film for food packaging applications.

Fruits & vegetables. Alginate-based food packaging is a preferred choice for fruits and vegetables due to its biodegradability, moisture retention, and potential to prolong shelf life. Li *et al.*, developed a sustainable food packaging film composed of fish scale-derived gelatin, sodium alginate, and carvacrol-loaded ZIF-8 nanoparticles. This film was UV-resistant, flexible, water-resistant, and had low water vapor permeability. It also exhibited strong antioxidant properties and sustained antibacterial activity against *E. coli* and *S. aureus*.[141]

Meat and beef. Alginate-based food packaging actually offers several benefits for meat and beef packaging, such as moisture control, freshness preservation, protection from contamination, and odour and flavor preservation. Guo *et al.*, improved sodium alginate matrix films for safe meat packaging by adding carboxylated cellulose nanocrystals and beet extract to increase the films mechanical strength and contribute to antioxidant and pH-sensitive properties.[133]

Cheese & bakery products. Alginate-based food packaging can be beneficial for cheese and bakery packaging, such as

Table 1 The application of alginate coating in food products based on their activity

Food product	Additives	Advantages	References
Anti-microbial activity			
Fresh-cut apple	$CaCl_2$ + thyme oil	Inhibition of growth of TPC 1, total coliform, LAB 1, yeast, and mold	[105]
Fresh-cut watermelon	Calcium lactate + *trans*-cinnamaldehyde	Effective against yeasts, psychrotrophs, coliforms, and molds	106
Fresh-cut pineapple	Sunflower oil + lemongrass essential oil	Growth inhibitory effect on yeast and mold, and increased shelf life	107
Strawberry	$CaCl_2$ + carvacrol + methyl cinnamate	Effective against *E. coli* and *B. cinereal*	108
Capsicum	$CaCl_2$ + pomegranate peel extract	Increased antibacterial and antifungal effects	109
Peeled and shallot onion	SA-CMC film + gluten blends + onion waste extracts	Improved water barrier property and tensile strength compared to SA-CMC film and reduced microbial load	110
Tomato	Aloe vera + garlic oil	Enhanced thermal and mechanical sproperties without affecting film transparency and improved antimicrobial properties	111
Chicken fillet	Galbanum gum + $CaCl_2$ + essential oil of *Ziziphora persica*	Significant microbial reduction was achieved with composite coating and EO addition to formulation	112
Chicken breast fillet	Alginate-maltodextrin $CaCl_2$-CMC + lactoperoxidase enzyme	Reduced the microbial loads of Enterobacteriaceae, *P. aeruginosa*, and aerobic mesophilic bacteria	113
Chicken meat	Alginate-whey protein + lactoperoxidase enzyme	Increased antimicrobial activity	114
Abalone	$CaCl_2$ + bamboo leaf extract + rosemary extract	Bacterial inhibition was improved	115
Chicken fillet	Chitosan + red beet anthocyanin extract	Enhance quality, shelf life, and microbial control	116
Rainbow trout fillet	$CaCl_2$ + resveratrol	Reduced the growth of bacteria, yeast, and mold	117
Silver carp fillet	Alginate-CMC + $CaCl_2$ + clove essential oil	Enhancement in antibacterial activity against *L. monocytogenes*, *S. aureus*, and *E. coli*	118
Bighead carp fillet	$CaCl_2$ + horsemint essential oil	Significant decrease in TVC and TPC growth rates	119
Sea bass	Tea polyphenols	Significant decrease in TVC growth rates	120
Sea bass, red sea bream	$CaCl_2$ + e-polylysine + 6-gingerol	Increase in antibacterial activity	121 and 122
Sea bass, fior di latte, cheese	$CaCl_2$ + reuterin (*Lactobacillus reuteri*)	Enhancement in antimicrobial activity	123 and 124
Kashar cheese	Alginate-whey protein + ginger essential oil	Bacteriostatic and bactericidal effect against *E. coli and S. aureus*	125
Mozzarella	$CaCl_2$ + potassium sorbate + sodium Benzoate + calcium lactate + calcium ascorbate	Reduced the growth rate of *Pseudomonas* spp. and Enterobacteriaceae	126
Low-fat cut cheese	Alginate-mandarin fiber + oregano essential oil	Antibacterial activity against *S. aureus,* psychrophilic bacteria, molds, and yeasts	127
	$CaCO_3$ + microencapsulated lemongrass oil	Decreased the growth rate of *E. coli and L. monocytogenes*	128
	Datura metel L. leaf extract	Significant antimicrobial activity against human pathogens	68
	CuO NPs + CNW	Excellent physicochemical, mechanical, and antimicrobial activity against food pathogens	129

Table 1 (*Contd.*)

Food product	Additives	Advantages	References
White mushrooms	Carvacrol (CAR) + β-cyclodextrin (βCD)	Improved water resistance, mechanical properties, light barrier properties, and heat aging. Films containing 30 g L^{-1} βCD-CARM were effective against *Trichoderma* sp.	130
Cheese	Silver spherical nanoparticles + lemongrass essential oil	Preserved cheese quality for 14 days and changed color to indicate storage conditions for sensitive food items	131
	Poly(diallyl dimethylammonium chloride)	Effectively inactivated 99.8% of SARS-CoV-2 within 1 minute of contact and exhibited inhibitory effects against *S. aureus* and *E. coli* bacteria	69
Antioxidant activity			
Longan	*Saccharomyces cerevisiae* + sucrose	Sucrose enhanced SE cell viability, improving the film's antioxidant properties during storage	132
Meat	Carboxylated cellulose nanocrystals + beetroot extract	High tensile strength and antioxidant capacity	133
	Gelatin-sodium alginate + aqueous beetroot peel extract	Limited microbial deterioration, delayed chemical oxidation, and improved sensory characteristics of the meat	134
	Gum kondagogu + glycerol	Blend films also exhibited high tensile strength (up to 24 MPa) compared to the pure biopolymer films	89
	Agar + glycerol + ascorbic acid	Increased tensile strength, transparency, and barrier properties against oxygen and water vapor	90
Guava	$CaCl_2$ + pomegranate peel extract	With the addition of pomegranate peel extract, enhanced the antioxidant activity	135
	Date palm pit extract incorporated into alginate-based films	The film with 40% DPPE exhibited the lowest retention of phenolic content, DPPH scavenging activity, and FRAP after a 3 months storage period	48
	Tannic acid	Increasing tannic acid concentration in the films improved water vapor barrier ability and antioxidant activity while decreasing light transmittance slightly	67
	Lycopene + β-carotene	Effectively protected sunflower oil from oxidation under accelerated storage conditions	136
	Grape pomace waste extract + $CaCl_2$	Protected food from light deterioration while maintaining water resistance and stability	64
Chicken fillet	Alginate-galbanum gum + $CaCl_2$ + *Ziziphora persica*	Due to their high phenolic and flavonoid contents, galbanum gum and *Ziziphora persica* contributed to significant antioxidant activities	137
Bream (fish)	$CaCl_2$ + vitamin C + tea polyphenols	Considerable reduction in TBA and lipid peroxidation	138
Red sea bream	6-Gingerol	Significant decrease in TBA and lipid peroxidation	122

Table 1 (*Contd.*)

Food product	Additives	Advantages	References
	Citrus pectin + pterostilbene	Improved moisture resistance and enhanced antioxidant properties	63
Bighead carp fillet	$CaCl_2$ + horsemint essential oil	After the eighth day of storage, EC led to decreased oxidation readings; the addition of horsemint EO further enhanced this effect	139
Silver carp fillet	$CaCl_2$ + clove essential oil	Considerable reduction in lipid peroxidation	118
Rainbow trout fillet	$CaCl_2$ + resveratrol	Significant decrease in lipid peroxidation	117
	Methyl methacrylate + ammonium persulphate initiators under a nitrogen gas atmosphere	Improved tensile strength, water resistance, thermal stability, and crystallinity	90
	Alginate-clay nanoparticles + $CaCl_2$ + lycopene	Decrease in FFA	140
Sea bass	Alginate + tea polyphenols	Decrease in lipid oxidation	120
Antibacterial activity			
Shrimp	Cubic Co-MOF microcrystals with ammonia-sensitivity	Improvement in mechanical strength, toughness, water/oxygen barrier and UV barrier property	70
Beef	Pectin + cinnamic acid	Exhibited 43.3% soil degradability in 15 days and preserved beef color better than control film during a 5 days test	65
	Pectin + calcium chloride + sodium citrate	Rough surface, exhibit effective antibacterial activity, and possess mechanical properties similar to commercial packaging films	49
	Cellulose nanocrystals + silver nanoparticles	Exhibited a plasmonic effect at 491 nm and provided excellent ultraviolet (UV) barrier properties	61
Combination activity			
(1) Antioxidant and antibacterial activity			
Strawberry	Fish scale-derived gelatin + carvacrol-loaded ZIF-8 nanoparticles	UV protection, increased flexibility, and reduced water vapor permeability. Strong antioxidant properties and long-lasting antibacterial effects against *E. coli and S. aureus*	141
Banana	Nitrogen-functionalized carbon dots + layered clay	Increasing UV blocking, antioxidant, and antibacterial activities by up to 70% and enhanced anti-browning activity	142
Beef and apple	Konjac glucomannan + tea polyphenols (TP)	Exhibited excellent microstructure, hydrogen bonding, improved mechanical and barrier properties, oxidation resistance, antibacterial activity, and stability	143
Bread	Sulfur quantum dots	Improved UV blocking by 82% and increased tensile strength by 18% Strong antioxidant and antibacterial effects, and prevented mold growth for 14 days	144
	Reduced graphene oxide or a mixture of zinc oxide-rGO (ZnO-rGO) + calcium chloride	Films with 50% ZnO-rGO showed high antioxidant and antibacterial activity, and low-temperature food sterilization	65

Table 1 (*Contd.*)

Food product	Additives	Advantages	References
(2) Antioxidant and antifungal activity			
Banana	Tea tree essential oil nano emulsion + TiO_2 nanoparticle	Excellent UV blocking and improved water vapor and oxygen barrier properties Improved banana postharvest quality and reduced anthracnose	60
(3) Antimicrobial and antioxidant activity			
Cheddar cheese	Carboxymethyl cellulose + *Thymus vulgaris* purified leaves extract	Good thermal stability, with improved prevention of moisture, acidity, puncture strength	145

acting as an oxygen barrier, retaining moisture, and preserving rind and flavor. Abdin *et al.*, developed biodegradable films from carboxymethylcellulose, sodium alginate and purified *Thymus vulgaris* leaf extract. The films exhibited good thermal stability and improved moisture content, acidity, puncture resistance and sensory properties of cheddar cheese during cold storage compared to commercial packaging materials.[145]

Sensory evaluation of edible films. Bersaneti *et al.* investigated the efficacy of a prebiotic edible coating, comprised starch and nystose, in preserving blackberries. The starch-nystose treatment significantly reduced microbial growth (molds, psychrotrophs, yeasts) after 7 days, maintaining counts within safe consumption levels. Both coatings prevented fruit softening (firmness) and pH increase, while preserving anthocyanin content. The sensory evaluation of blackberries coated with the starch-nystose edible film showed good acceptance and purchase intention, without significant differences compared to uncoated control samples. These findings suggested a promising and sustainable approach (biodegradable coating) for extending the shelf life of blackberry and preserving quality.[158] Ribeiro *et al.* evaluated the use of *Persea americana* (avocado) pulp extract in edible coatings for minimally processed Fuji apples. The ethanol-extracted pulp extract, analyzed by GC-MS, was incorporated into alginate and chitosan-based coatings. Microscopic evaluation revealed the alginate coating effectiveness in inhibiting enzymatic browning and enhancing apple appearance. Sensory analysis showed the alginate coating with the extract achieved the highest, extending shelf life of the apples by 15 days. This suggested the potential for avocado pulp extract as a natural ingredient in coatings to improve apple quality and shelf life.[159] Pavli *et al.*, investigated the potential of SA edible films as carriers for probiotic bacteria in sliced ham, with and without high pressure processing (HPP) pretreatment. The films, containing three probiotic strains, were applied to ham slices, and stored at varying temperatures. Microbiological, pH, and color analyses were conducted alongside sensory evaluations. The presence and abundance of each probiotic strain were assessed using pulsed field gel electrophoresis. In untreated ham slices, probiotic counts exceeded 106 CFU g^{-1} across all storage temperatures. Similar results were observed in HPP-treated samples, though these exhibited higher pH values. Sensory analysis indicated a more acidic taste and odour in probiotic samples compared to controls, with these characteristics notably diminished in HPP-treated samples. The study concluded that the edible films effectively delivered probiotics to the products, irrespective of HPP treatment, which indicated promising results for probiotic delivery.[160] Zarandi *et al.* demonstrated a study on the impact of a composite coating of SA, galbanum gum (GG), and hydroalcoholic nettle extract (NE) on the quality of refrigerated rainbow trout fillets. The coating was applied to fillets under 10 different conditions, with NE concentrations varying from 0 to 1%. The study found that the coating, particularly at 1% NE concentration, effectively slowed chemical and microbial spoilage. This was attributed to lower lipid oxidation and microbial deterioration in coated fillets at the end of the 12 days period. Sensory evaluation revealed that the composite coating helped maintain the fillet quality throughout the storage period. This suggested that the SA-GG composite coating with NE can enhance the sensory properties of refrigerated rainbow trout fillets, in addition to delaying lipid oxidation and microbial spoilage. This highlighted the potential of such coatings in preserving the sensory and physical quality of refrigerated fish products.[161] Serrano *et al.*, developed edible films derived from starch, intended for use as wrappers. These films were designed to prevent moisture migration from the filling of a tortilla, while preserving its physicochemical and sensory attributes. The mechanical attributes of films made from corn and pea starch were assessed through measures such as tensile strength (ranging from 22.34 to 27.5 kPa), elongation at break (varying from 53.20 to 185.96%), and Young's modulus (spanning from 64.35 to 17.09 MPa). The findings demonstrated that the films derived from pea starch enhanced robustness and adaptability in contrast to their corn starch counterparts. This was primarily due to the influence of the amylose content and molecular mass. A sensory assessment revealed that the pea starch film was successful in reducing the moisture transfer from the filling to the tortilla. This resulted in the maintenance of the tortilla texture, visual appeal, and sensory characteristics for a duration of 6 days, thereby enhancing the overall gastronomic experience associated with this food item.[162]

Table 2 Alginate based functional films composition for food packaging applications

Polymers	Added fillers	Composition	Properties	Application	Reference
Alginate/CMC/starch	—	—	The enhanced water vapor barrier and mechanical strength are enhanced. Grape shelf life increased during storage, up to several weeks	Blue and green grapes packaging	146
Alginate	Melanin and zinc oxide/silver nanoparticles	Melanin: 0.10%, 0.25% and 0.50% *w*/*w* Silver and zinc oxide nanoparticles (10 mM film casting solutions for both metal nanoparticles)	Improved water vapor barrier characteristics, mechanical strength, enhanced antioxidant/ antimicrobial activity, and improved UV radiation barrier capabilities	Active food packaging	147
Alginate/CMC/starch	Grapefruit seed extract	1 : 1 : 1 (alginate : CMC : starch)	Improved antioxidant/ antimicrobial and UV barrier qualities. Green chilies have an extended shelf life of 25 days during storage	Chilli packaging	148
Alginate	Aloe vera (AV) and garlic oil (GO)	AV gel: 0, 50 and 66.7 wt% Garlic oil: 0, 1.0%, 3.0% and 5.0% v/w	Protective UV protection increased antibacterial activity, and enhanced shelf life of coated tomato	Active packaging	149
Alginate	Hallocyte (Hal) derived from Dragon and Dunino mines loaded with salicylic acid	—	Improved antimicrobial characteristics than pectin-based films. Antibiotic activities against food spoilage bacteria	Active packaging	150
Alginate	Sulfur quantum dots	—	Increased UV light barrier characteristics, antioxidant/ antibacterial activity, and mechanical strength. Ideal for bread packaging that extends its shelf life for up to two weeks	Bread packaging application	151
Alginate	Copper sulfide nanoparticles	0.0, 0.5, 1.0, and 1.5 wt%	Improved UV barrier, hydrophobicity, mechanical strength, and antibacterial resistance to Gram-negative bacteria	Active food packaging	152
Alginate	Sulfur nanoparticles	1%, 2%, and 3% w/w	Improved mechanical strength, hydrophobicity, and antimicrobial resistance against Gram-negative bacteria	Active packaging	153
Alginate	Cottonseed protein. Hydrolysates (CPH)	0%, 0.15%, 0.30% and 0.60% (w/v)	Produced films containing antimicrobial activity against Gram-positive bacteria and fungi. Sustained release of CPH compounds	Active packaging	154
Alginate	Cellulose nanocrystal, silver	1 wt%	High UV barrier properties, increased tensile strength, and decreased water vapor permeation than neat alginate films, have high UV barrier properties	Food packaging	155
Sodium alginate	Cellulose nanowhisker, copper oxide nanoparticles	CNW (0.5%)–SA (3%)–CuNPs (5 mM)	Excellent antibacterial activity against food pathogens, challenging antioxidant activity	Active food packaging	156
Alginate	Halloysite nanotubes and zinc oxide nanoparticles	1, 3, 5, and 7 wt%	Superior mechanical, UV-light, and water vapor barrier properties. Antibiotic activity against foodborne pathogens	Active packaging	157

Market outlook. Public acceptance of biopolymers in food packaging is crucial, necessitating education on their benefits and safety. Despite the current preference for petroleum-based materials due to their superior performance and lower cost, their environmental impact is significant. The commercialization of eco-friendly, biodegradable packaging can greatly benefit countries relying on landfills for waste management. Therefore, the promotion of renewable material-based packages is essential. Recent advancements in food packaging have explored cost-effective options, such as blending expensive alginates with other biopolymers and developing biopolymer nanocomposites. Despite numerous studies on alginate packaging, consumer hesitation persists, underscoring the need for public awareness of biopolymers advantages over plastics. Alginate packaging not only promotes the use of biodegradable materials but also ensures food safety and maintains product quality.[163] Botalo *et al.*, formulated intelligent edible coatings and films, exhibiting superior UV barrier characteristics, derived from alginate, whey protein isolate, and curcumin. These films showed a substantial decrease in the rate of water vapor transmission and experienced a reversible color transition from orange to red upon exposure to ammonia vapor.[164] Edible coatings and films derived from alginate have been employed to enhance and preserve the quality of various food items such as fruits, vegetables, meats, poultry, seafood, and cheese. These applications contribute to the increased shelf-life by mitigating dehydration, regulating respiration, enhancing product aesthetics, and enhancing mechanical properties, among other benefits.[165] Sodium alginate films are used to cover meat products to prevent the loss of color and texture.[166] Films based on alginate, recognized for their complete biodegradability and edibility, have traditionally been utilized as packaging materials for water-soluble powdered products. These include items such as coffee, coffee-related specialties, instant teas, and powdered milk.[167] These films provide a sustainable and eco-friendly alternative to traditional packaging materials.

Techno-economic assessment. The manufacture of edible films necessitates a multifaceted approach, incorporating various essential raw materials. Alginate, a polysaccharide derived from brown seaweed, constitutes a crucial component, with its cost per kilogram fluctuating between $10 and $50, contingent upon quality and sourcing methodologies. Plasticizers, such as sorbitol or glycerol, are commonly employed to enhance the flexibility and elasticity of edible films, with bulk purchase prices ranging from $1 to $5 per kilogram. Crosslinking agents, including $CaCl_2$ or sodium alginate, contribute to the improved mechanical strength and stability of these films, priced between $2 and $10 per kilogram. Natural colorants and flavorants are added to enhance the visual appeal and taste of edible films, with costs varying from $5 to $20 per kilogram. The incorporation of antimicrobial agents, such as organic acids or essential oils, for food safety and shelf-life increase, may range from $10 to $50 per kilogram. Furthermore, thickeners, stabilizers, surfactants, preservatives, and emulsifiers play vital roles in the production process, with costs spanning $5 to $20 per kilogram. Moreover, the equipment costs for alginate extraction and film-forming machinery can amount to $100 000 to $500 000, highlighting the complexity and expense involved in forming edible films for diverse applications.[168,169]

Future scope. The use of alginate-based materials in food packaging is a promising advancement in the field of sustainable food preservation. Scientists are attempting to improve the barrier properties of alginate films to increase their resistance to oxygen, moisture, and UV light.[170] The concept of active packaging, in which alginate films are infused with antimicrobial agents or antioxidants, is a promising solution to preserve food freshness and quality. Nanotechnology could potentially contribute to the development of nanocomposites that combine the beneficial properties of alginate and nanoparticles to improve barrier properties and overall functionality.[171] Research is currently underway on personalized packaging solutions to preserve various foods most efficiently such as fruits, vegetables, and meats. At the same time, sustainable sourcing methods for alginate, such as growing algae, are being considered to build a reliable and environmentally conscious supply chain. In addition, the introduction of optimized recycling methods for alginate-based packaging materials will help reduce waste and promote environmental protection. Establishing industry standards and regulations for alginate-based packaging is critical to ensure its safety and quality and strengthens its position in the sustainable packaging sector.[172]

Conclusion

Alginate-based food packaging materials have significant potential for applications in the food industry. Their inherent biodegradability, compatibility with biological systems, and ability to enhance the longevity of a wide variety of products make them a viable and effective sustainable choice. However, further research and development efforts are needed to optimize their properties and increase production so that they can be widely used. Indeed, given the increasing demand for environmentally sustainable packaging, there is significant potential for alginate-based solutions to help reduce plastic waste and promote a more environmentally conscious approach to food packaging. The future of food packaging looks promising with the emergence of such innovative and sustainable solution.

Data availability

The data supporting this article have been included as part of the ESI.†

Conflicts of interest

There are no conflicts to declare.

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